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## Use of New Generation Instruments in Measurement of New Steam Expander

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### ABSTRACT

For the past twenty years the Centre for Positive Displacement Compressor Technology, at City University, has employed experimental techniques for the measurement of screw compressors' performance where both experimental data and predicted mathematical models are found to be in agreement with each other. Some of the experimental measuring techniques involve the use of pressure and temperature transducers installed in the housing to determine the vital thermodynamic process characteristics and functioning performance of compressors.

Moreover, as advanced technologies were available, measurements were performed in an optical compressor with a transparent window near the discharge port to allow the application of a laser technique, Laser Doppler Velocimetry (LDV), to investigate the axial mean flow and turbulence characteristics inside the working chamber of the male rotor.

Recently a prototype two-phase screw steam expander has been designed and developed as a means of power recovery from liquid geothermal brine. An experimental setup has been designed by using a set of new generation instruments to complement the unit's numerical modeling, from which predictions of an adiabatic efficiency in the order of 70%, were obtained. The testing includes measurements of instantaneous pressure and temperature in the suction and discharge port, instantaneous torque, speed and flow rate as well as monitoring the temperature and pressure of its lubrication system. Furthermore, four miniature high resolution pressure transducers were installed in the expander unit to measure the main rotor inter lobe temporal pressures with respect to crank angle of the main rotor. The high dynamic characteristics and response of the instrument are captured by a real time processor, National Instrument Compact-RIO, data logger and the programming is done using LabVIEW.

The paper presents the measuring method, preparation of the instruments, acquisition and processing of the results obtained during experimental investigation of the two-phase screw expander.

### 1. INTRODUCTION

The growing concern over security of fossil fuel and energy related emissions of CO<sub>2</sub> that, unchecked, could more than double by 2050, has given a strong incentive towards the utilisation of low carbon energy technologies especially from renewable sources. Extracting energy from geothermal resources is known for its reliable production of base-load power in areas where geological conditions permit fluids to transfer heat from the Earth to the surface at high temperatures. Such resources can be used in binary power plants, combined heat and power plants or in heat-only applications. Emerging geothermal technologies, that extract energy from the hot rock resources found everywhere in the world, hold much promise for the expanded production of geothermal power and heat.

One of the major costs arising from geothermal power plant is drilling. Any improvement in harnessing the energy more efficiently, by increasing the output, from such system is therefore advantageous for both investors and the

environment. It had been shown that flash expansion to derive dry steam from liquid geothermal resources leads to a large loss in power recovery potential (Smith *et al.*, 2001).

Early work carried out during the late nineteen seventies in an attempt to recover the power loss with two-phase screw expanders proved to be ineffective due to both their low adiabatic efficiencies or their relatively high manufacturing cost. As technologies have advanced, it is now possible to make more successful screw expanders. This has been achieved through three key developments, namely: (a) improved understanding of the expansion process (b) advances in rotor profiling and (c) the introduction of advanced machine tools capable of making high precision rotors at an economic cost.

As an outcome of a long term research programme, carried out at City University, London, the two-phase expansion processes based on the use of the screw machine has been well mastered and the operation is now far better understood. In an early work of the authors, Smith and Stosic (1995), it was found that the key feature to obtaining high adiabatic efficiencies with screw expanders is for the built in volume ratio of the machine to be substantially less than the actual volumetric expansion ratio of the fluid being expanded. Moreover, the use of a special rotor profile developed by Stosic (1996) made screw expander far more reliable to run without the need of external timing gear to avoid rotor contact or oil flooding of the working chamber.

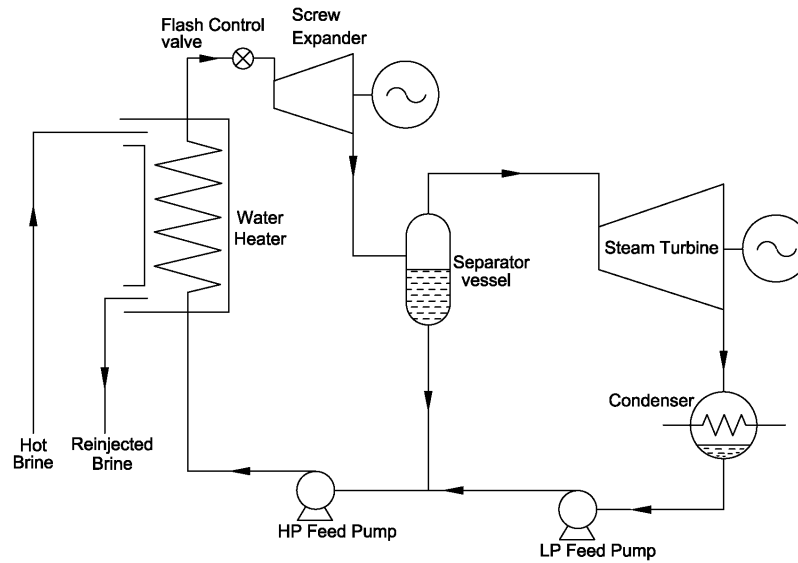
One proposal to develop and sell electrical power, derived from heat recovered from geothermal sources by a means of a heat extraction method known as Hot Fractured Rock (HFR), was brought to the attention of the authors. The thermal power plant to convert the recovered heat to electrical power is best described as a closed cycle flash steam systems. This involves circulating clean water in a separate closed circuit, where the water is first pressurised, recovers heat from the geothermal brine in a heat exchanger and is then flashed through a throttling valve to a lower pressure, where any steam formed from the flashing process is separated from the water and further expanded in a turbine to produce power. The expanded steam is then condensed, partially pressurised, mixed with the water separated from the steam, and then re-pressurised to re-enter the brine heat exchanger. As shown in Fig 1, the power output and efficiency of such a system could be increased by 12-20% by recovering power from the depressurising process in a suitable type of mechanical expander, rather than by throttling it.

Therefore, to augment the steam turbine power output, it was decided to use a screw expander, as a means of augmenting the power recovery. City University London who has more than twenty-five years of experience in this field was approached. A preliminary feasibility study was carried to determine what additional power could be obtained in a 1 MW demonstration, at the design conditions specified, with a screw expander replacing the throttle valve, using the authors' SCORPATH software (Smith *et al.*, 1996) This showed that the inclusion of the screw expander could raise the total system output to 1.2 MW. To establish the performance of such system it was planned to build a pilot plant of this output gave an opportunity for the technology to be proven.

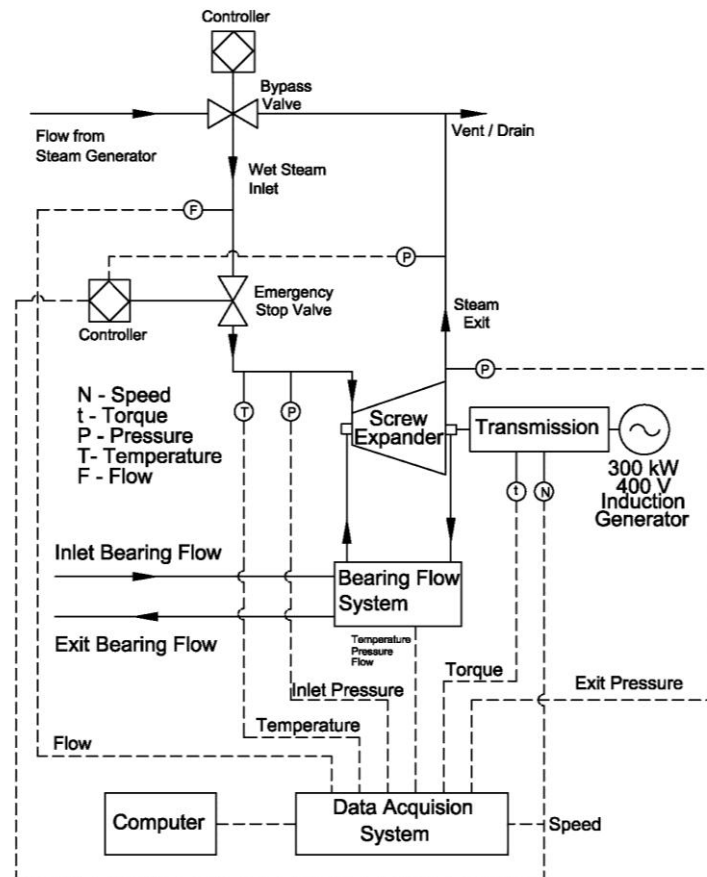
City University has designed and built a two-phase expander to be made as an additional feature of the 1MW unit. It has been estimated that the expander would have an adiabatic efficiency of about 70% and a power output of 250 kW and it would be located, as shown in Figure 1. The machine is of novel design and, as far as is known, is the first of its type to be made specifically for inclusion in a geothermal power plant in which water is used both as the working fluid and as the expander lubricant. Moreover, this machine runs on water lubricated bearings thus eradicating oil wholly in the system. In order to complement the predicted results obtained for the prototype machine, it was necessary to investigate experimentally all the vital thermodynamic parameters and its functioning performances. An instrumentation system was fitted to enable the performance of the whole unit to be monitored and controlled by computer. This consisted of a flow meter, a transmission torque and speed meter to measure the expander shaft output, pressure and temperature recording instruments to measure the inlet and outlet conditions, and a set of specialised piezoresistive pressure transducers to record the pressure changes within the expander working chamber as the expansion process proceeds. Also additional flow meters, pressure transducers and thermocouple were installed to monitor and control the bearing lubrication system.

Before delivering the screw expander to the power plant, it was the authors' wish to test its mechanical reliability and as well as to carry out extensive tests to check whether the machine needed modifications or adjustments, should the unit not operate as expected. However, it was found that using hot water at the operating conditions of the geothermal plant would be too expensive. Instead, a wet steam test facility was used to reproduce similar bearing

and rotor loads to that of the geothermal site. This paper describes the experimental procedures and presents the results obtained with wet steam where they are compared to the predicted mathematical ones.



**Figure 1:** Basic layout of closed cycle single flash pilot plant



**Figure 2:** Two phase expander test rig

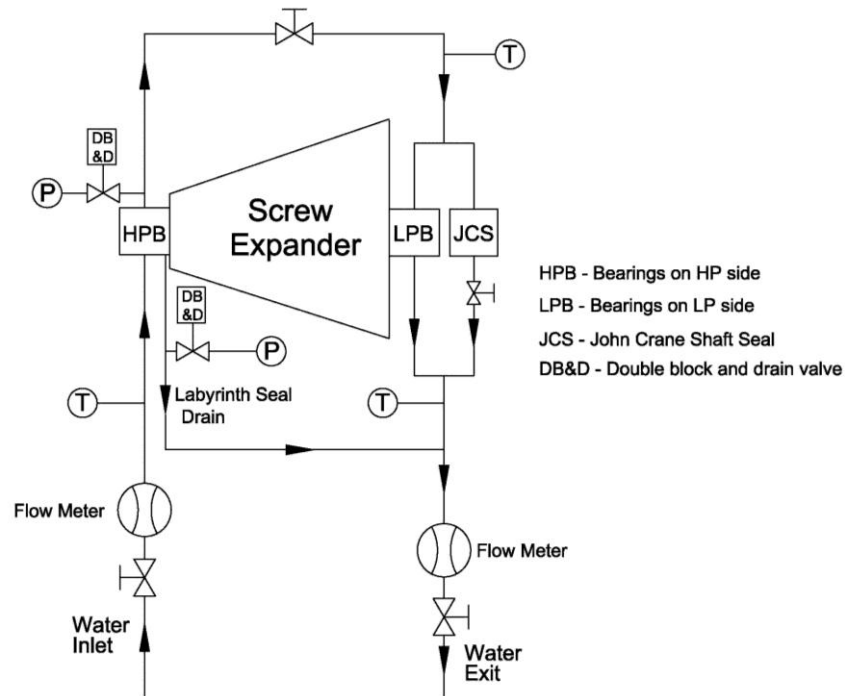


Figure 3: Bearing system for two phase expander

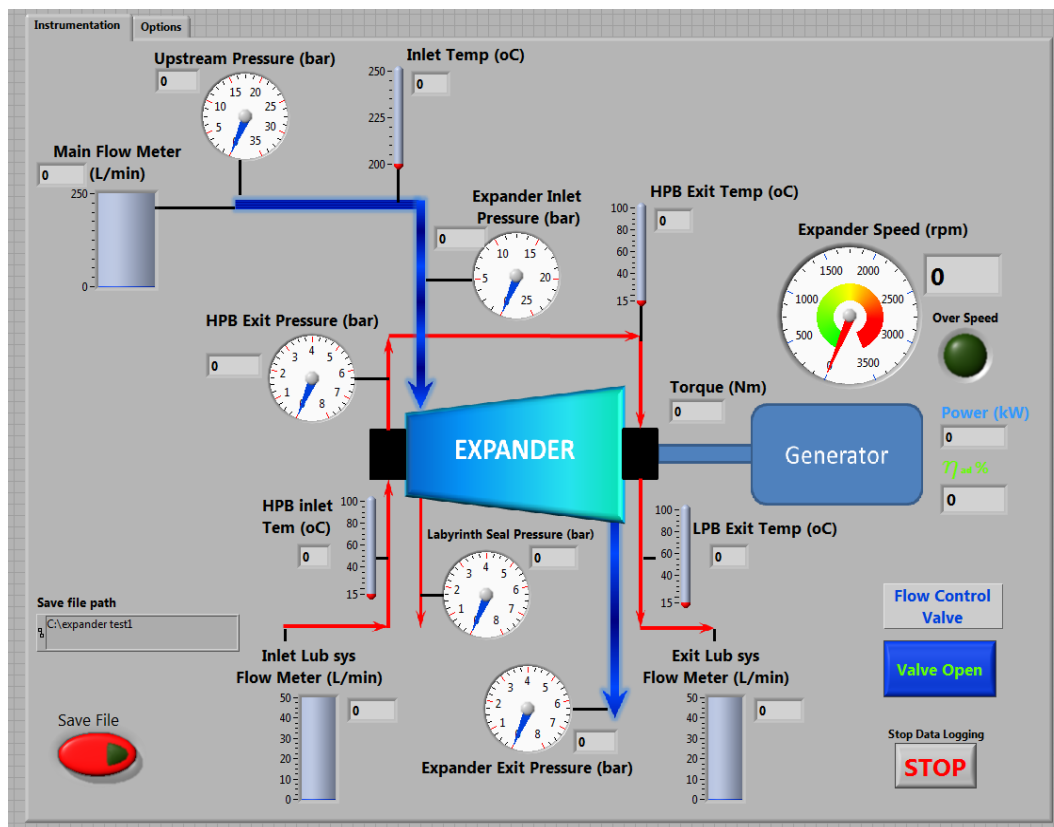


Figure 4: Graphical user interface of the expander unit monitoring and control

## 2. TEST RIG AND MEASURING INSTRUMENTS

Figure 2 depicts a schematic presentation of the screw expander test rig. The system essentially comprises a twin screw expander with water lubricated bearings, as displayed in figure 3, which is coupled to an induction generator to convert the expander mechanical shaft power to electrical power output. Where available, suitable recognised design codes have been used as a guide in the building of the expander. However, there are some aspects of the design for which such codes were inappropriate or where no suitable codes exist. In these cases, design decisions have been made on a rational basis, using software and other analytical tools, developed in house, and based on nearly thirty years of R and D work carried out on screw expanders. The machine has been designed to expand the entire flow from the geothermal power plant primary heat exchanger from inlet conditions, given as pressurised hot water at 213.5°C and 33 bar, down to an exit pressure of 6.5 bar, at a flow rate of 24.72 kg/s.

The whole unit is mounted on a purpose built frame designed to comply with BS EN 2573 standards and to withstand earthquake and other environmental effects. The rotors are of, “N” profile, 4-5 configuration, made of C1045 steel bar where the main rotor diameter is 234mm and L/D ratio of 1.55:1. The rotor lobes have been ground finished to a tolerance of  $\pm 5$  microns and then coated to minimise contact friction and enhance lubrication. The casing of the expander is made of carbon cast steel, and complies with API Standard 619-1997 for the design of rotary type positive displacement compressors for petroleum, chemical and gas industry services. The bearings are of the hydrodynamic type and water lubricated. These are of a proprietary type, designed to resist the estimated bearing loads, based on SCORPATH calculations. The bearings were designed to enable hard contact to be made, during repeated start up and shut down, without significant damage. During the running of the expander, the bearings had a continuously supply of water to maintain the load carrying capacity for the rotors as well as keeping a constant surface temperature of the bearings.

The expander output shaft power is measured from a dual torque and speed transducer. The transducer, strain gauge type, is a non-contact rotary unit with remote transmission to a stator. One end of the shaft of the transducer is connected to the expander output shaft through a torque limiter coupling and the other end is connected to the electric motor through a sprag clutch. The torque transducer has been calibrated for 0 to 1400 Nm and its speed 0 to 3600 rpm. Steam is admitted to the inlet of the expander by a steam generator and controlled by a pneumatically driven control valve located just before the inlet. The valve, was adapted to act as an emergency stop valve, in the event of over speeding or loss of external load. The opening and closing of the control valve is carried out by a pneumatic valve actuator with an electropneumatic positioner, EP5. The positioner compares the electrical signal from the controller, with the actual valve position and varies the pneumatic output signal to the actuator accordingly. One of the expander exit pressure transmitters is connected to the controller. The desired valve position is therefore maintained for any control signal and the effects of varying differential pressure. Commonly, this is known as a P to P positioner since it takes a pneumatic signal (P) from the control system and provides a resultant pneumatic output signal (P) to move the actuator. A supply of 4 barg air is connected to the positioner. The controller can also be placed in manual mode to proportionate the valve opening. The control valve emergency shutdown can be activated manually from either a remote panel button or data acquisition software. Also the emergency shutdown of the control valve will occur automatically in the event of expander over speeding. The default over speed limit is set to 3100 rpm and this can be changed to the desired over speed limit. For this test, the water/steam mixture leaving the expander is discharged to the drain and not recirculated.

The inlet and exit pressure of the expander is monitored by pressure transmitters where they are mounted via a double block and bleed valve manifold. The pressure transmitter is a silicon strain gauge microsensor which converts the pressure to a change in resistance which in turn is proportional to the applied pressure. The inlet temperature is measured by a platinum resistance thermometer (or RTD) which is mounted into a thermowell device. The change in temperature will result in a change in electrical resistance of the platinum wire of the temperature device. The change of resistance in both pressure and temperature devices is converted to a 4 to 20 mA current signal where they are then linked to the data acquisition system. The pressure and temperature of the bearing lubrication system is also monitored and recorded and its instrumentation can be seen in figure 3.

The expander inlet water flow rate is measured with a Turbine flow meter, fitted in a housing with ANSI 600 3” flange end connections. However, for the wet steam experiment its flow rate was obtained from the boiler control system. The inlet and exit water bearing lubrication flow rate are measured with another Turbine flow meter. Both flow meters consist of a ferritic stainless steel rotor that revolves within a nonmagnetic housing on the outside of

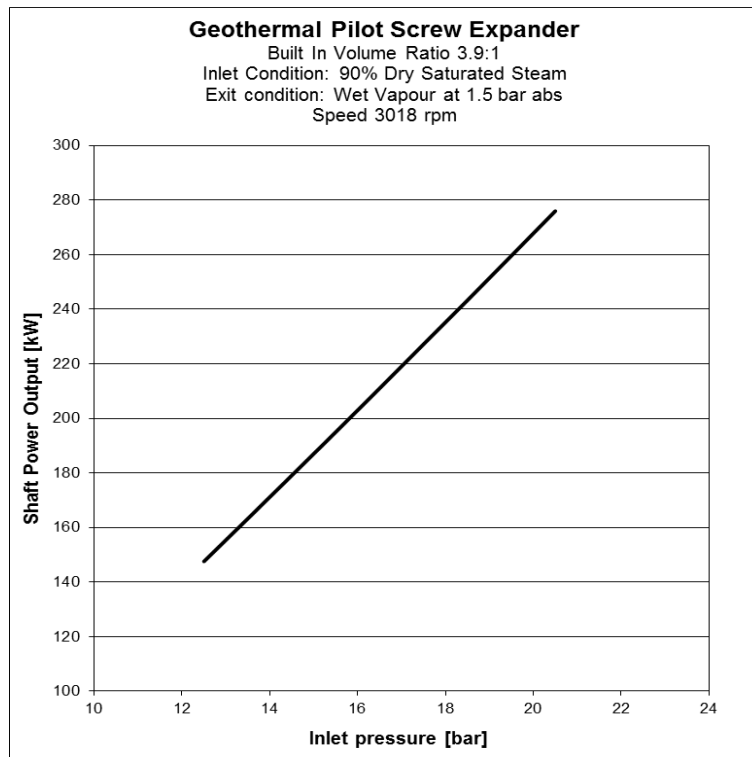
which is located a pick up coil containing a permanent magnet. As the rotor blades pass the tip of the permanent magnet, the reluctance of the magnetic circuit is changed, and a small A.C. voltage is generated in the coil. The frequency of the A.C. voltage is proportional to flow rate, and the total number of pulses produced represents total flow passed through the meter. The output sinusoidal pulse is converted to digital pulses through a signal conditioner and sent to the data acquisition system. Four pressure gauges, were installed in the expander unit to measure the main rotor inter lobe temporal pressures with respect to rotation of the main rotor. The transducers are miniature silicon diaphragm pressure sensors capable operating at high temperatures. The measurements obtained from these pressure devices are not presented in this paper.

A data acquisition system has been used to acquire signals from the measurement transducers during the experiment. It consists of a National Instrument Compact-RIO (CRIO-9022) Real-Time with an 8 slots chassis CRIO-9114. It features an industrial 533 MHz real-time processor for deterministic, reliable real-time applications and contains 256 MB of DDR2 RAM and 2 GB of non-volatile storage for holding programs and logging data. The unit also permits the acquisition of signals from the measurement transducers simultaneously during the experiment that are inputs to the unit itself and connected to a computer via an Ethernet cable. The chassis of the system has five modules:

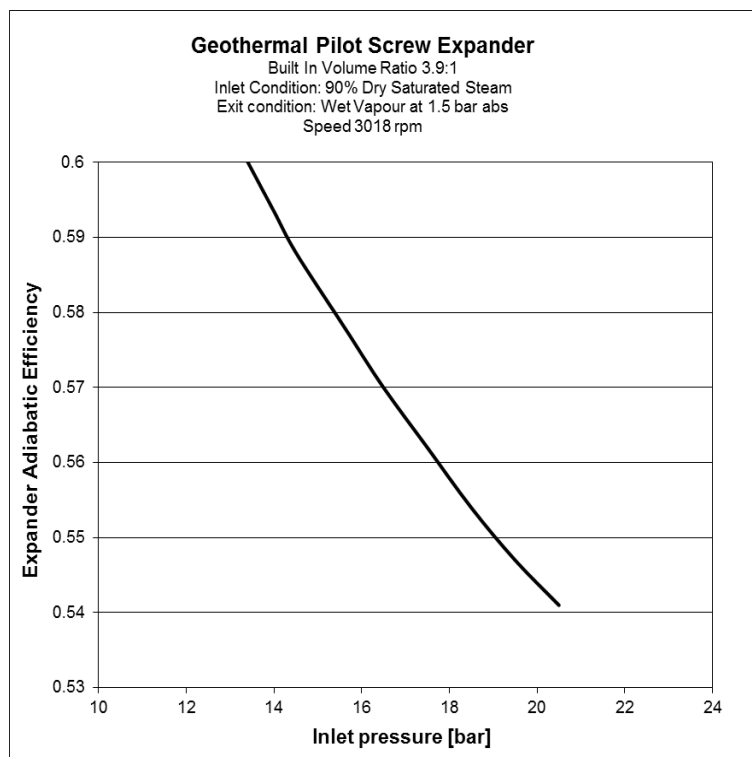
- (1) NI-9217: 4 100  $\Omega$  RTD analogue inputs
- (2) NI-9203: 8 analogue inputs
- (3) NI-9237: 4 analogue inputs with half or full bridge
- (4) NI-9401: 4 digital inputs/outputs
- (5) NI-9871: 4 ports RS422/RS485

The programming is carried out using LabVIEW FPGA (Field Programmable Gate Array). This was a requirement so as to facilitate communication with the existing data acquisition system of the geothermal power plant. The measurements obtained from the transducers are displayed on the computer via the graphical user interface (GUI) as shown in figure 4. The shaft output power and adiabatic efficiency of the expander were automatically computed, based on the inputs of the measurement transducers, and were also displayed on the GUI. The measurements can be saved into the computer at any time during the running of the expander.

To start the expander test, the lubricating water circulating pump is started and the flow control globe valve is adjusted to the flow required conditions. The controller of the flow control valve is set to maintain an expander exit pressure of 1.5 bar where the valve is initially kept close to prevent any steam leaking into the expander. The boiler is started and then its throttle valve is set to the pre-recorded conditions in order to obtain the desired mass flow rate exit pressure. The induction generator is connected to the mains so that it is motored up to its asynchronous speed, operating as a motor. The bypass flow control valve is slowly closed. As this takes place, the flow control valve does gradually open automatically and the expander will start to rotate so as to maintain the required expander exit pressure. At some point, soon after the start of the closing of the bypass flow control valve, the expander speed will equal that of the already rotating generator. Further closing will then lead to the speed of the generator increasing and the change of its action from motoring to generating with electrical power fed into the mains. The process is continued until the bypass flow control valve is fully closed and all the steam flows through the expander. When the bypass throttle valve is fully closed, adjustments must be made to the boiler feed pump and burner controls to achieve the desired flow rate, pressure and dryness fraction of the wet steam delivered to the expander. When steady state operation is achieved for the desired inlet and exit conditions, data logged by the expander instruments, together with the power output and efficiency, derived from the measurements, is recorded and saved to the computer.

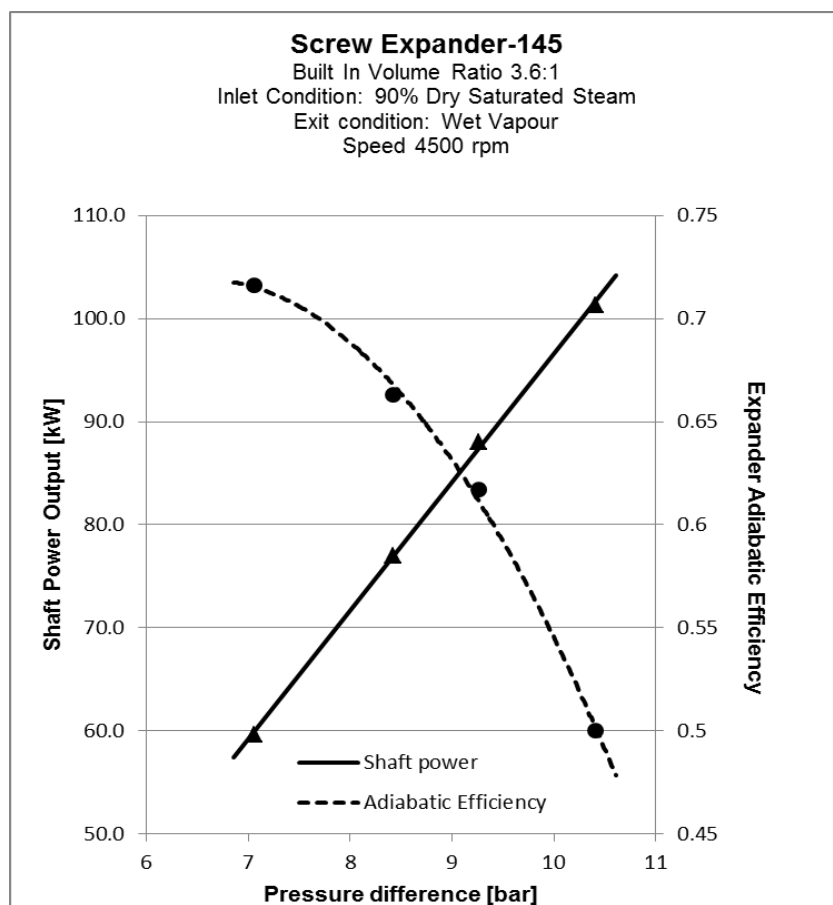


**Figure 5:** Predicted shaft power output when expanding wet steam



**Figure 6:** Predicted adiabatic efficiency when expanding wet steam





**Figure 7:** Measured shaft power output and adiabatic efficiency of 145 mm screw expander

### 3. RESULTS AND DISCUSSION

Figure 5 and 6 show the performance estimates obtained from the authors' expander simulation software, developed in house, with admission of 90% dry saturated steam and assuming an exit pressure of 1.5 bar. These predicted results are for the running of the expander at the test facility. It can be seen from the above graphs as the differential pressure increases the expander shaft output power increases, as expected, but at the expense of efficiency. As can be seen, the predicted performance is rather below the values set for the design condition, when operating with pressurized hot water at the inlet. This is due to the built in volume of the machine being set for the much larger volume change associated with two-phase expansion from pure liquid and therefore leads to under expansion of the wet steam.

Upon starting the expander with wet steam the readings obtained by the data acquisition system from the instrumentations seems to be working as anticipated and were found comparable to visual gauges. At the time of writing the paper the test rig suffered a malfunction and hence it was not possible to achieve the desired test conditions. Experimental data, using wet steam, were obtained from another prototype screw expander and are presented instead. This machine has similar design and building approach to the aforementioned one, except that it has smaller rotors and run on oil lubricated bearings. Figure 7 shows a plotted graph of the measured shaft power output and adiabatic efficiency as a function of pressure difference between the expander inlet and outlet. The shaft power output incremented with increasing pressure difference where as its adiabatic efficiency decreased and it can be seen to have similar behaviour to the predicted results of the geothermal screw expander.

#### 4. CONCLUSIONS

The authors have taken up the challenge of building the expander unit for the recovery of power from geothermal resources. It is strongly believed that this design is unique of its kind where it has been developed entirely as an expander rather than the reverse of a compressor. In addition to the design of the machine, much time and effort have been employed in installing the instrumentation and programming of the data acquisition which made the entire unit an in-situ laboratory. The new generation of instrumentation used for the measurement of this novel expander has worked satisfactorily as per the algorithm. Wet steam as working fluid was employed in the screw expander and the following observations were made:

1. A larger pressure difference between the expander inlet and outlet resulted in larger expander power.
2. The trend of the experimental results can be in some way comparable to the predicted results of the geothermal machine.

Furthermore, based on the steam experiment test results obtained by the smaller screw expander, the authors believe that the feasibility of such application in geothermal power recovery would be a success.

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